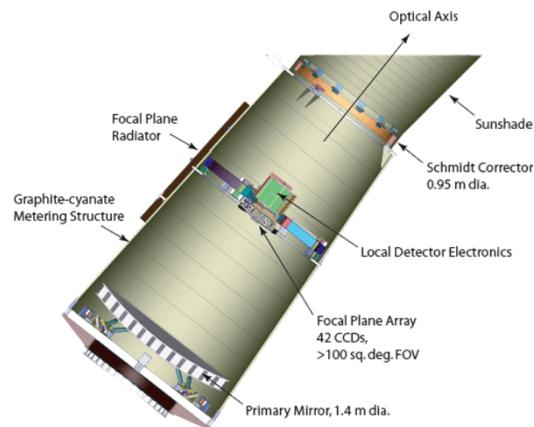




Eta-Sub-Earth Projection from Kepler Data

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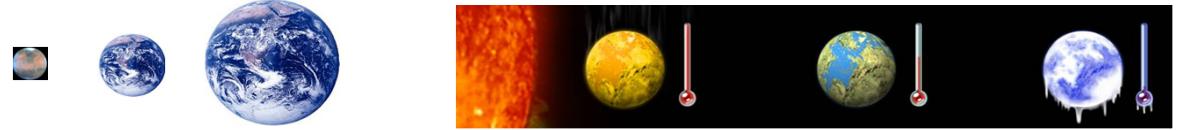
AAS Meeting, Austin
9 January 2012



What on Earth is η_{\oplus} (eta-sub-Earth)?

η_{\oplus} = number of habitable planets / number of stars

habitable planet = terrestrial body in the HZ
= $(0.5 \leq r/r_{\oplus} \leq 2.0)$ & $(\sim a_{Venus} \leq a/L^{1/2} \leq \sim a_{Mars})$



Example:

Including potentially habitable planets, $\eta_{\oplus} \approx 3$ in the Solar System.

The Kepler database (the “sample”)

11 Feb. 2011 database covers mission quarters Q1,2,3 = 136 days

153,196 target stars

20,406 F stars ($T_s = 6000\text{-}6500\text{ K}$)

55,595 G stars ($T_s = 5500\text{-}6000\text{ K}$)

37,643 K stars ($T_s = 5000\text{-}5500\text{ K}$)

113,644 total

1235 planets (“planetary candidates”)

159 F-star planets

475 G-star planets

325 K-star planets

959 total

Period sampling is complete up to $136/3 \sim 42$ day periods.

Bias estimation

Actionable items:

1. magnitude-limit bias
2. period-completeness bias
3. transit-probability bias

Signature:

$n_p \downarrow$ as mag \uparrow
search algorithm
transit sample

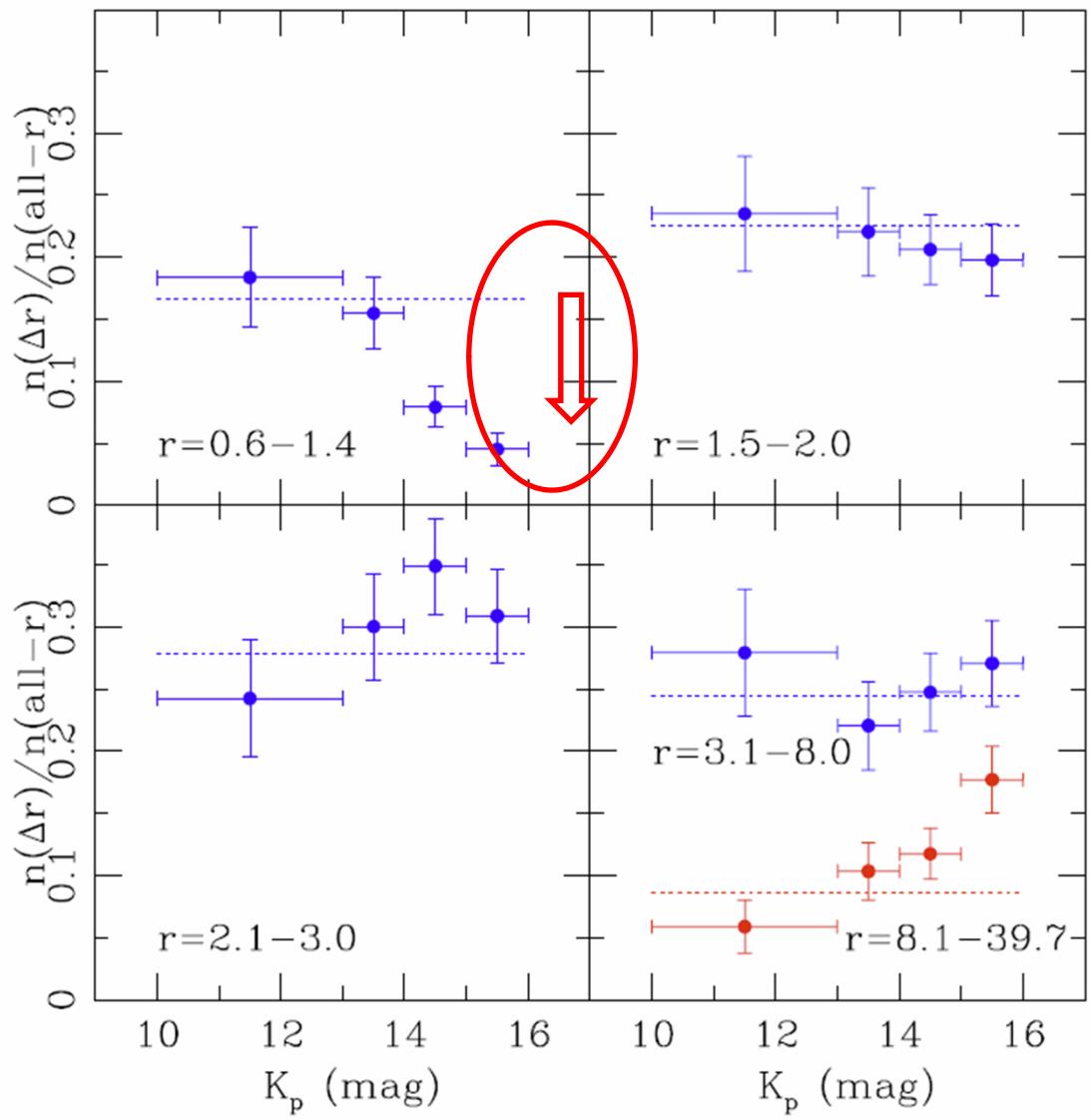
Action taken:

use mag < 14 only
use $P < 42$ days only
scale each planet by $1/p_t$

Ignored potential items:

4. field-of-view bias
5. active-star bias
6. star-spot bias
7. stellar-parameter bias
8. spectral class bias
9. impact-parameter bias
10. false-positive bias
11. distribution-function bias
12. mission-length bias

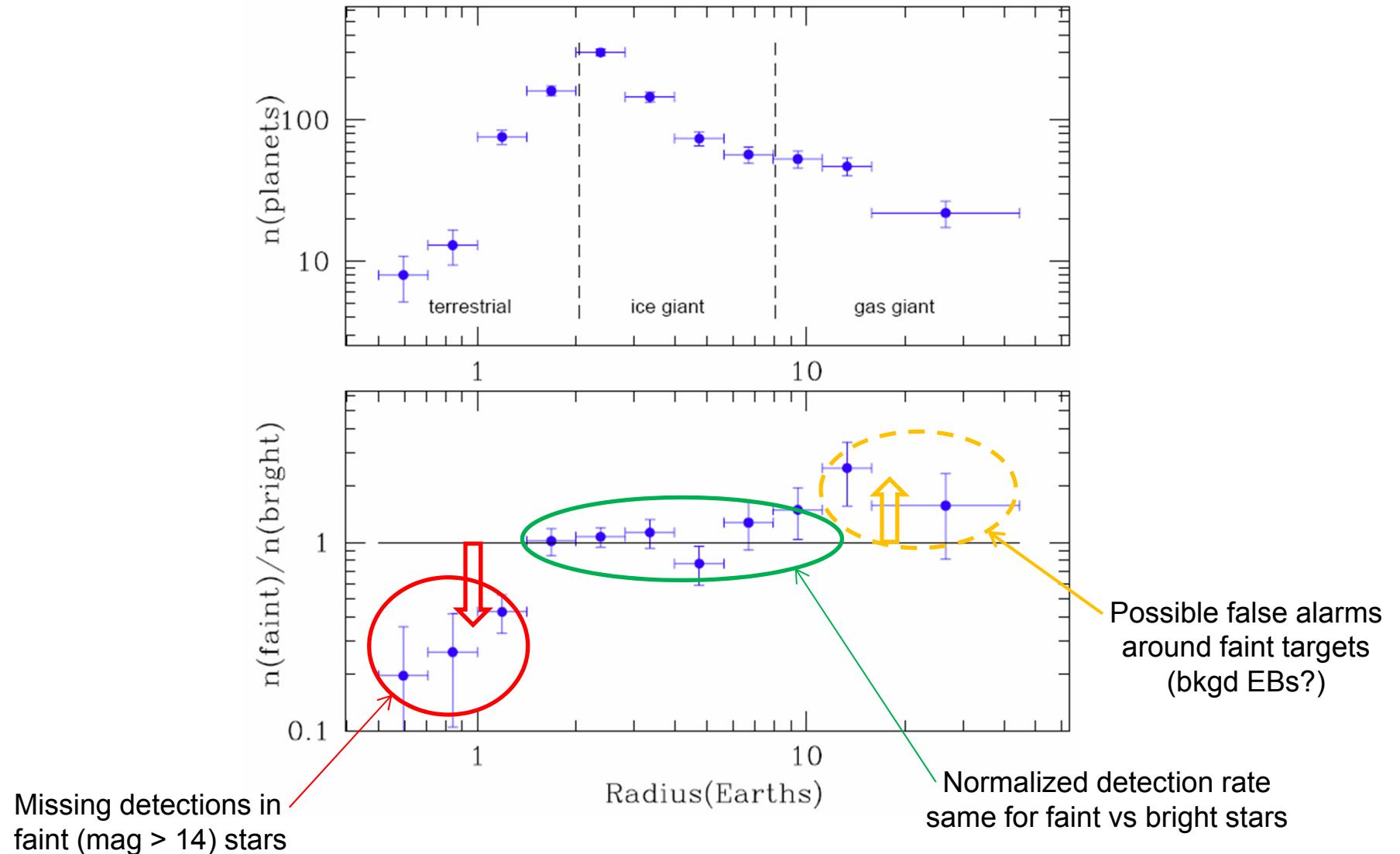
1. Magnitude-limit bias



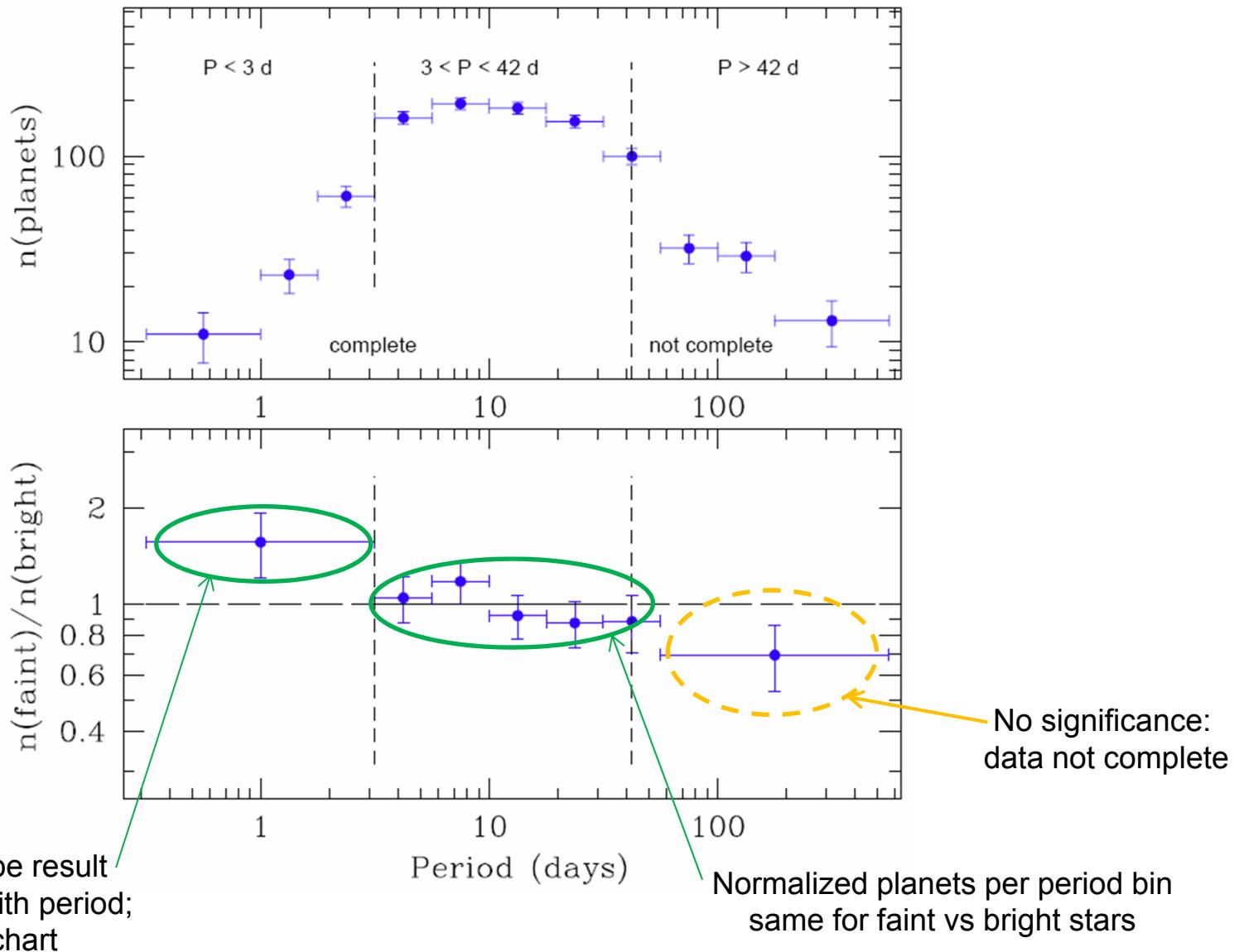
Signature:
 $n_p \downarrow$ for mag > 14

Action:
keep only mag < 14 stars

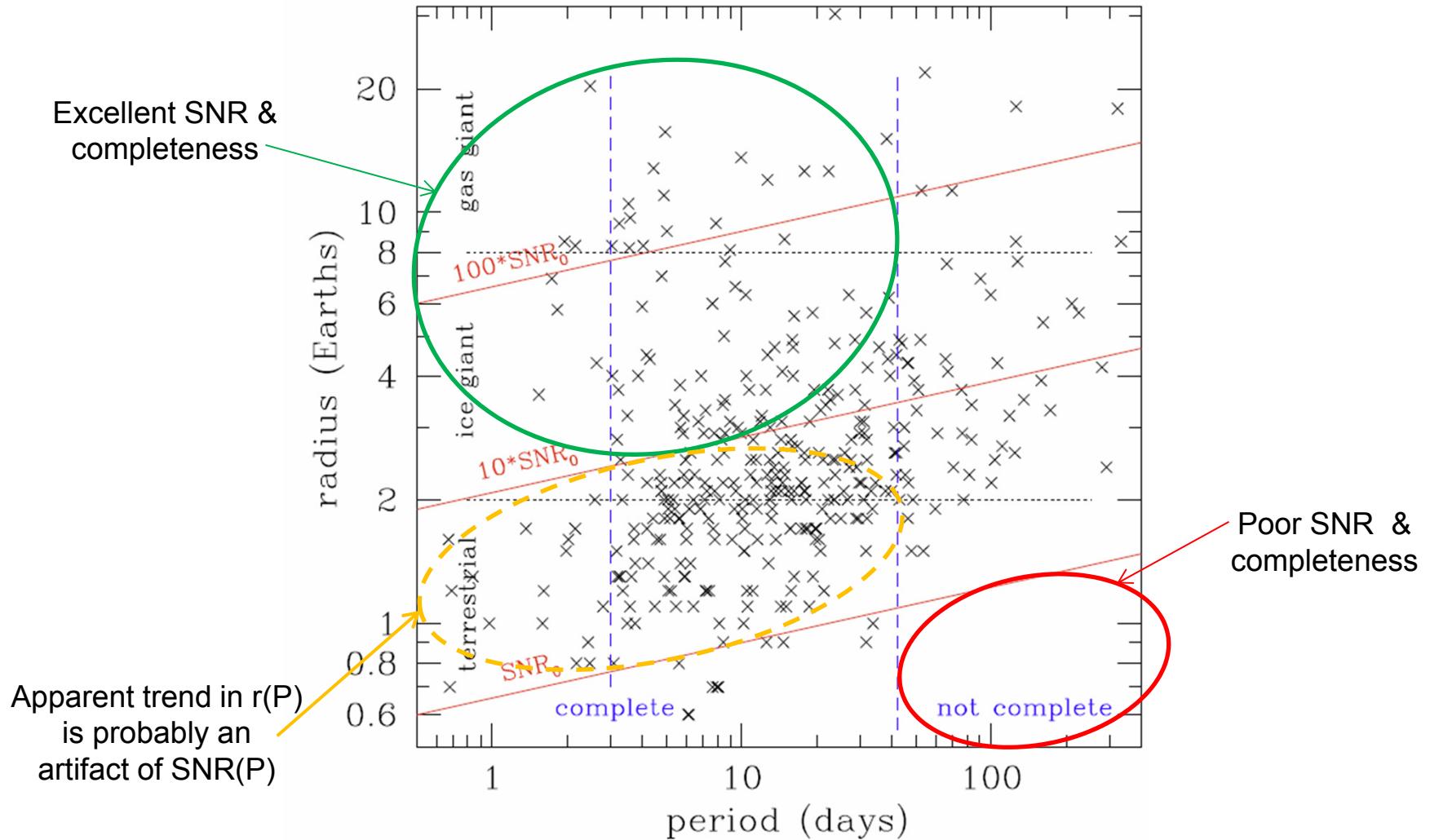
1-cont.: Magnitude-limit bias, n_p vs r



2. Period-completeness bias



Biases 1 & 2 combined: $n_p(P, r)$ vs SNR



Habitable zone

Wide HZ: 0.72 AU (Venus) to 2.00 AU (Mars 1.52 +)
ensures including all conceivable planets that could be habitable

Nominal HZ: 0.80 AU to 1.80 AU
recommended by TPF-C project in 2006, a “best bet”

Narrow HZ: 0.95 AU to 1.67 AU
gives a lower limit on η_{\oplus} , to make sure we build TPF large enough

Convert from Sun to other star period using

$$a \sim L^{0.5}$$

and $L \sim M^{3.8}$

and $P^2 \sim a^3/M$

so **$P(\text{days}) = 365 \cdot M^{2.35} \cdot a_{\text{sun}}^{-1.5}$**

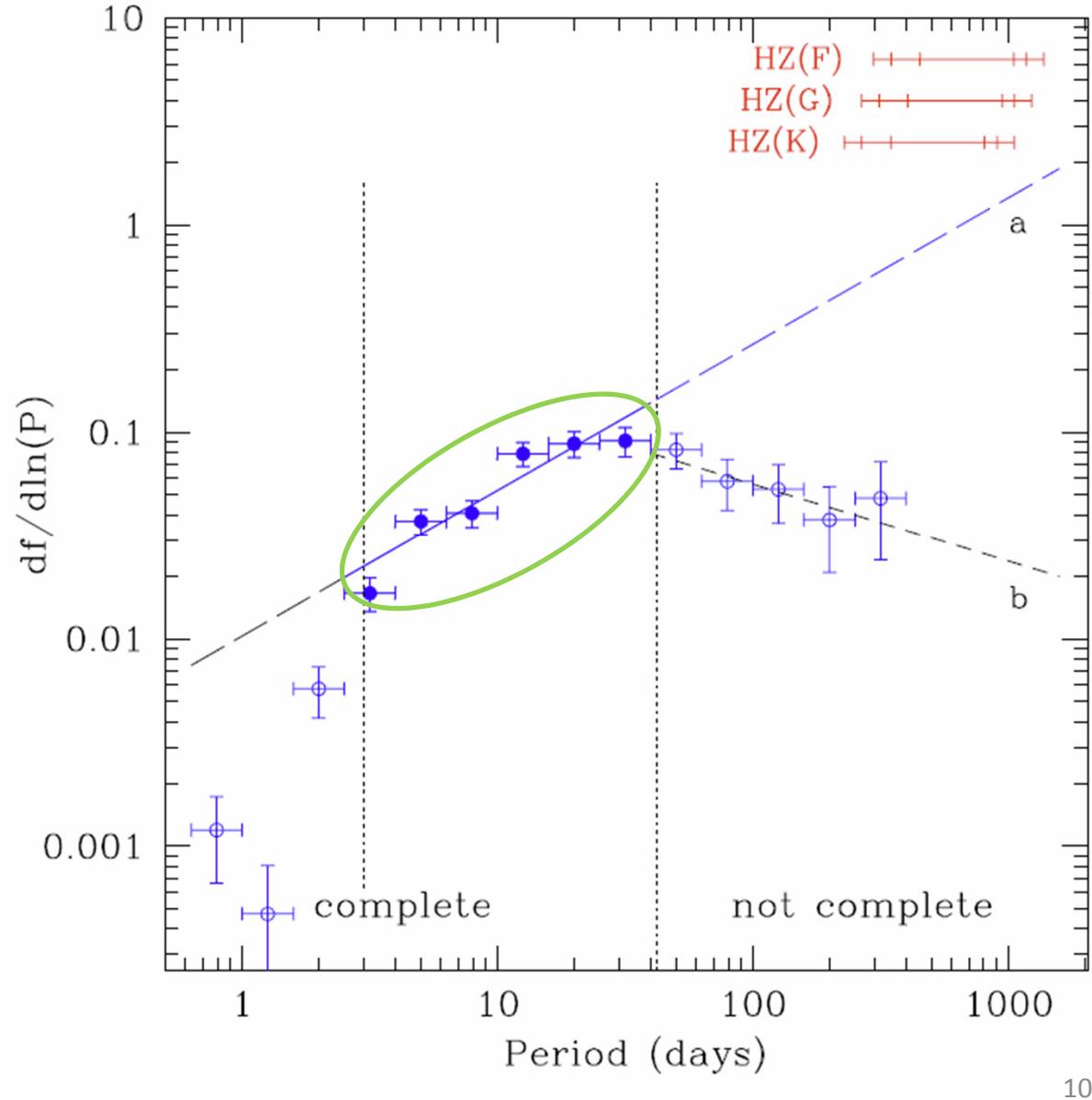
$$d[N_p(P)/N_{stars}] / d\ln(P)$$

prob. of transit:
 $p_t = R(\text{star})/a(\text{orbit})$

So:
 $N_p = 1/p_t(1) + \dots$
 $+ 1/p_t(n_{\text{sample}})$

Set:
 $f = N_p/N_{stars}$

Assume fit:
 $df/d\ln(P) = A \cdot P^\beta$



η_{\oplus} calculation

Integrating all planets under the extrapolated curve gives

$$f_2 - f_1 = A(P_2^\beta - P_1^\beta) / \beta$$

Specialize to terrestrial fraction:

$$\rho_{\oplus} = N_p(\text{terr}) / N_p \cong 0.29$$

so net result is

$$\eta_{\oplus} = \rho_{\oplus} \cdot A \cdot (P_2^\beta - P_1^\beta) / \beta$$

HZ type	$\eta_{\oplus}(F)$	$\eta_{\oplus}(G)$	$\eta_{\oplus}(K)$
Case 1	0.47	0.44	0.39
Case 2	0.37	0.34	0.31
Case 3	0.27	0.25	0.22

Averaging over the HZs and spectral classes gives

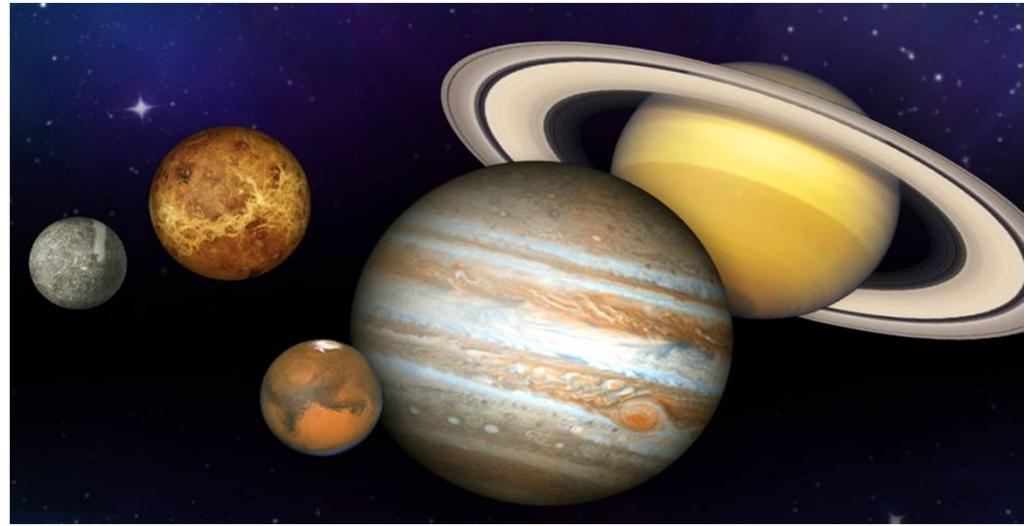
$$\eta_{\oplus} = 34 \pm 14 \%$$

Thank you!

Exoplanets: where & how many?

Outline of talk:

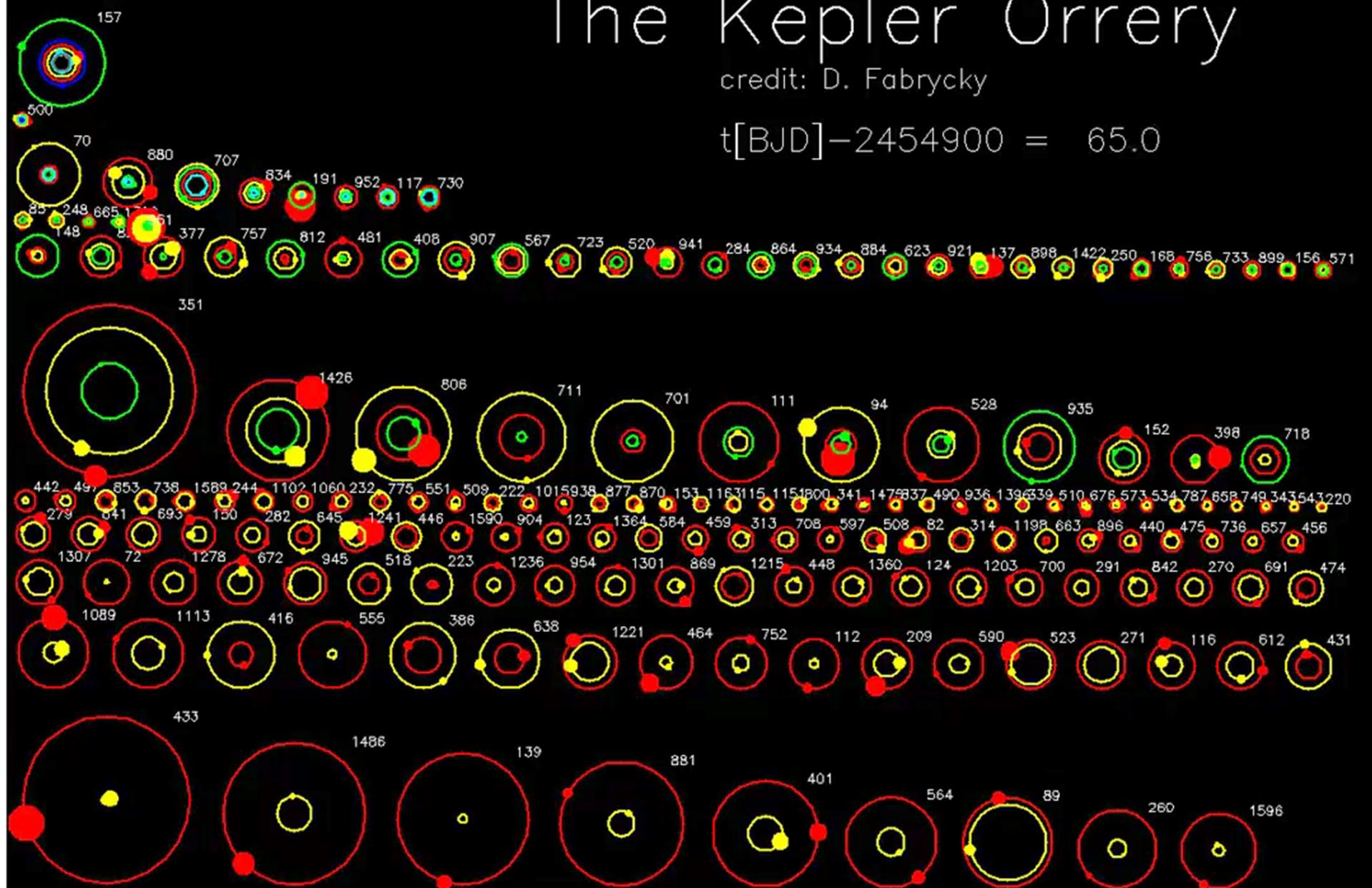
- The Kepler database
- Biases
- The radius distribution
- The period distribution
- Projecting from the sample to the population
- Extrapolating the period distribution
- The Habitable Zone
- Calculating the number of terrestrial, HZ planets
- Conclusions



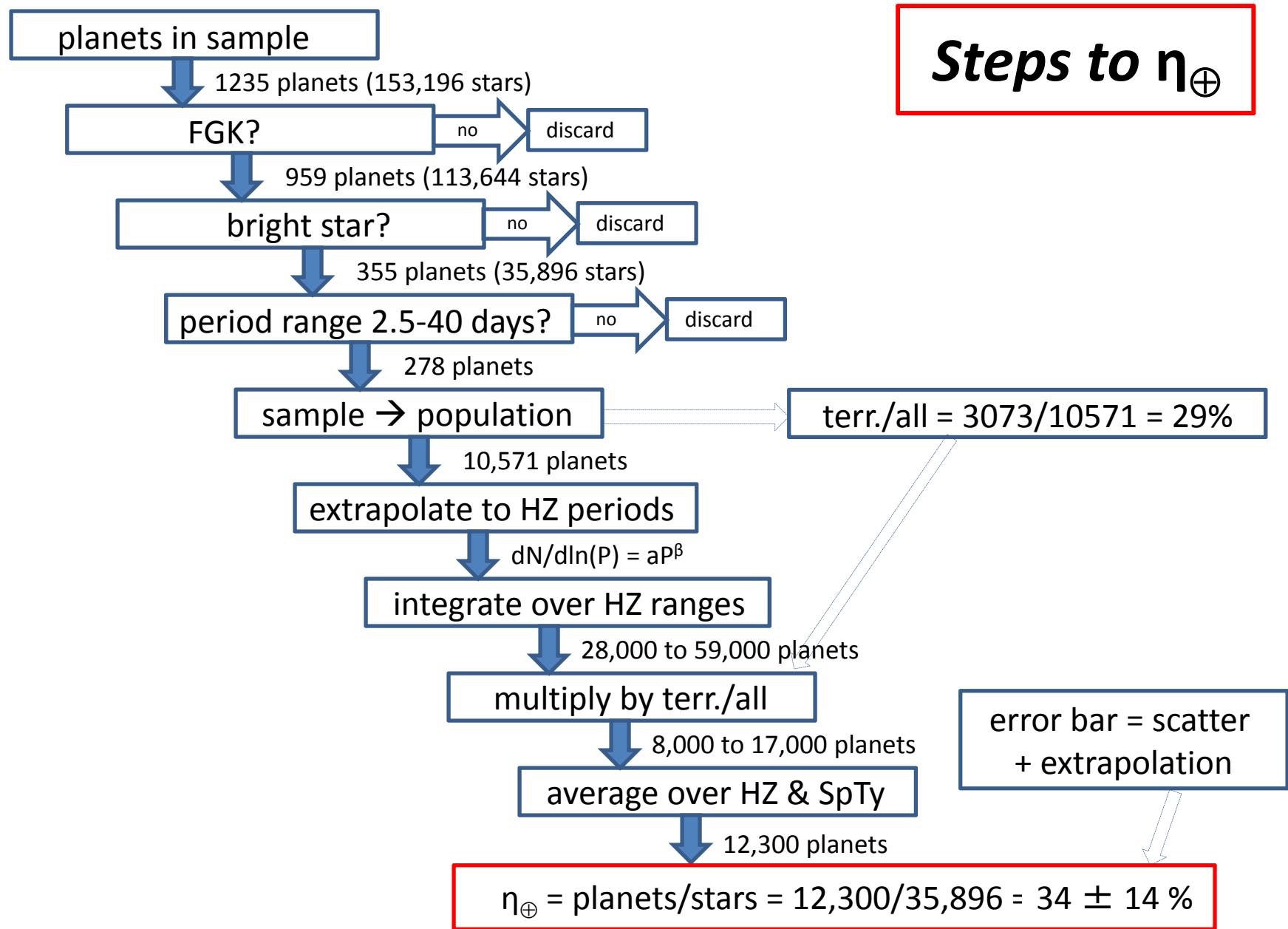
The Kepler Orrery

credit: D. Fabrycky

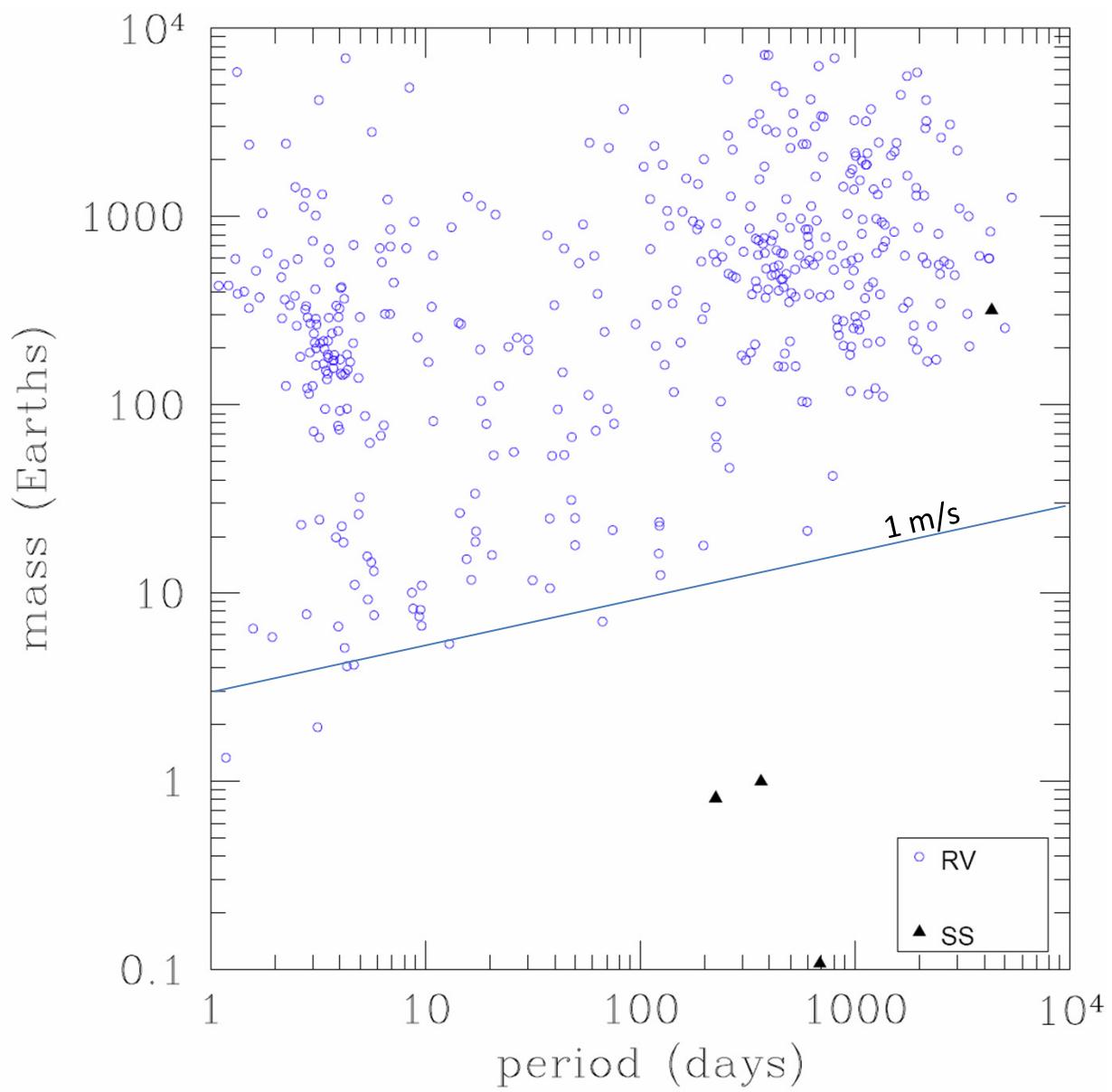
$t[\text{BJD}] - 2454900 = 65.0$



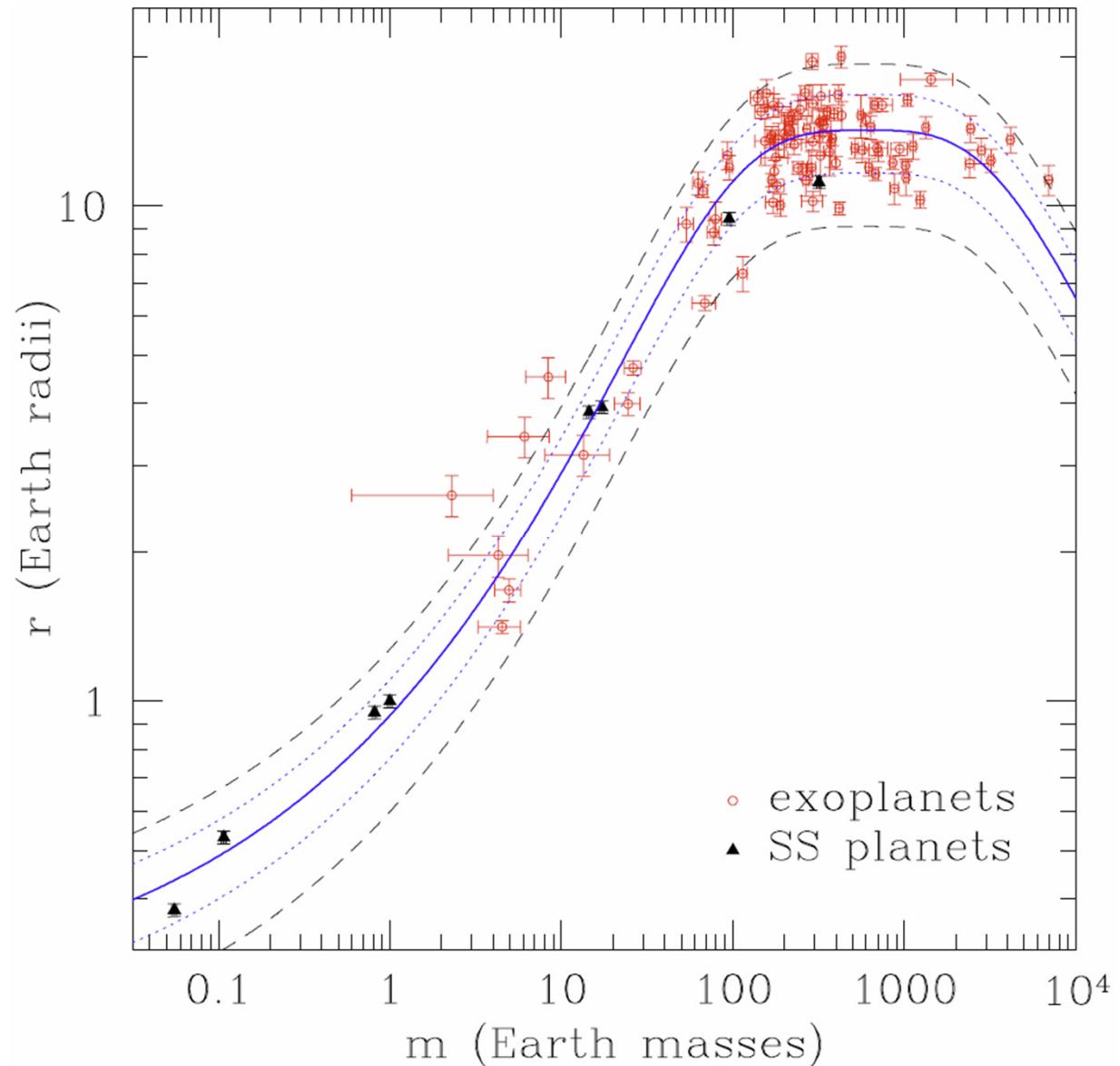
Steps to η_{\oplus}



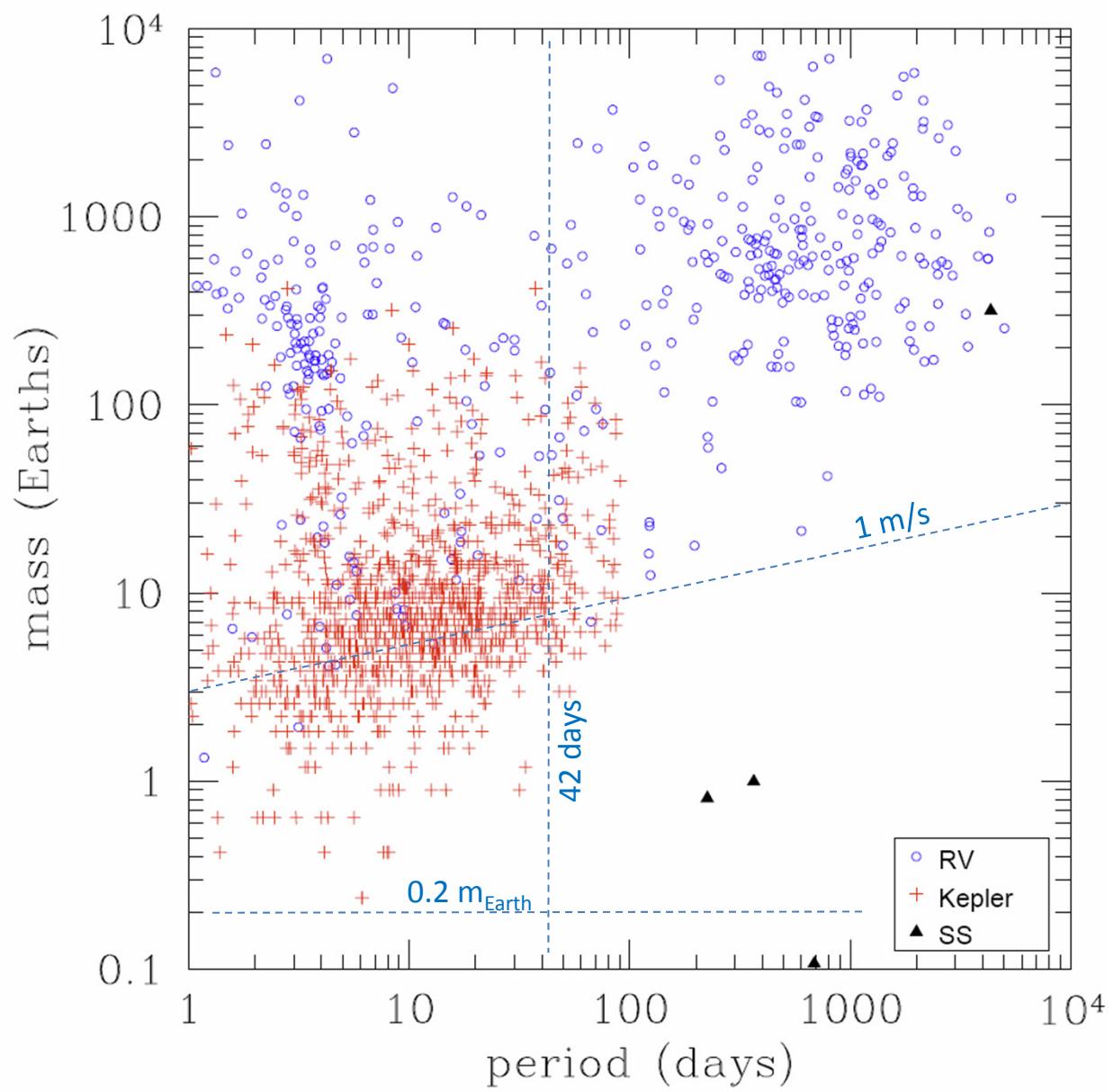
Mass vs period from RV



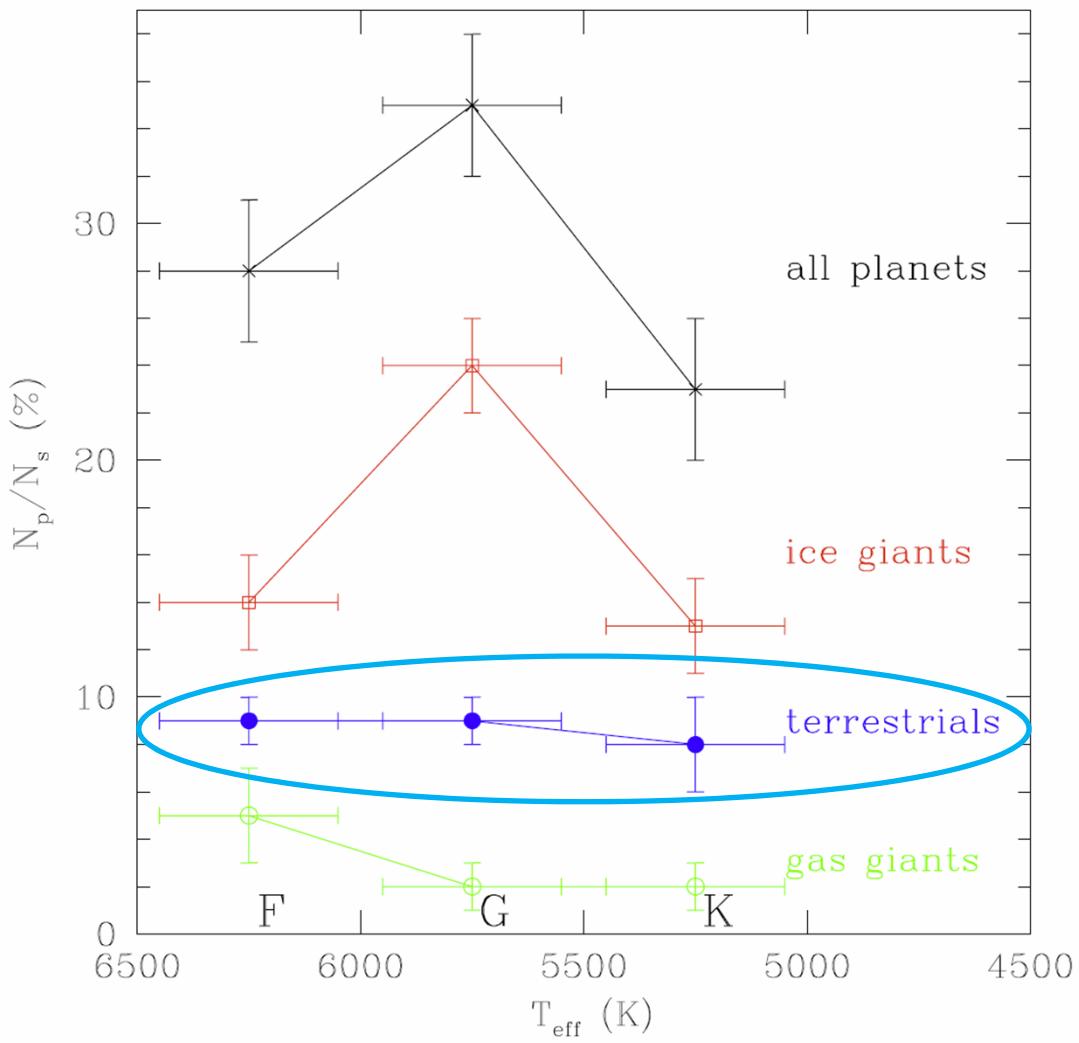
Radius vs mass from transits+RV



Mass vs period from RV & Kepler



Planet types vs star spectral types in population



SpTy	$\frac{N_p(\text{terr})}{N_s} (\%)$	$\frac{N_p(\text{ice})}{N_s} (\%)$	$\frac{N_p(\text{gas})}{N_s} (\%)$	$\frac{N_p(\text{all})}{N_s} (\%)$
F	9 ± 1	14 ± 2	5 ± 2	28 ± 3
G	9 ± 1	24 ± 2	2 ± 1	35 ± 3
K	8 ± 2	13 ± 2	2 ± 1	23 ± 3
FGK	9 ± 1	18 ± 1	3 ± 1	29 ± 2

Close-in ($P < 42$ days),
terrestrial-size planets
are found around about
9% of each of F, G, K stars.